Deformation and metasomatism in the sub-continental lithospheric mantle of the Carpathian-Pannonian region (Hungary) and Jeju Island (South Korea)

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Introduction

The basic principle of plate tectonics and its relationship to volcanism is common knowledge yet in order to better understand in details one must consider the upper mantle as the origin and driving mechanism of these processes. Results of the past decades on melt generation, percolation and related metasomatic processes, along with the recognition that fabric analysis and crystallographic preferred orientation of constituent minerals has come to the foreground in recent studies on deep lithospheric rock samples inspired us to gain additional information on such well-known and widely inferred processes as deformation and metasomatism of the upper mantle, as well as melt-volatile immiscibility at high PT conditions. For such purposes, two peridotite xenolith series became available from the sub-continental lithospheric mantle of the Carpathian-Pannonian region and that of the Jeju Island showing clear evidences for either metasomatism with melt percolation or deformation, or both. The Carpathian-Pannonian region (CPR), which consists of a group of young extensional basins, in the eastern neighborhood of the Alpine orogen belt is situated on an extremely thinned continental lithosphere and it is one of the geologically best studied areas in the world (*e.g.* Csontos & Vörös, 2004, Horváth *et al.*, 2006, Bada *et al.*, 2007 and references therein). The fact that orogenic and extensional processes here are relatively young and that there is a massive body of knowledge on geology, geochemistry, geophysics, volcanism and sediments provides us a unique natural laboratory to study the evolution of the upper mantle. Besides, upper mantle peridotites from the sub-continental lithospheric mantle of the CPR are extensively studied (see Szabó *et al.*, 2004 for a summary), due to the Neogene alkali basaltic volcanism transporting large amount of xenoliths to the surface. Majority of these papers focuses on the central part of the CPR, particularly on the Bakony-Balaton Highland Volcanic Field (BBHVF), thus a broad geochemical and petrophysical database, as well as a solid knowledge has become available to outline the general composition and evolution of the sub-continental lithospheric mantle beneath the CPR. Nevertheless, special samples are needed to study deformation and metasomatism, two processes which widely occur in upper mantle and might significantly change its physico-chemial properties. We have selected two amphibole-bearing metasomatized spinel peridotites, which enclose coexisting silicate melt and fluid inclusions from the BBHVF, because they uniquely encapsulate metasomatism as is. Similarly, three deformed, flattened tabular equigranular spinel peridotites have been studied in details to better understand the deformation processes in the shallow sub-continental lithospheric mantle of the BBHVF. Although, the number and uniqueness of these selected xenoliths does not allow us to draw general conclusions on the physical state and geochemical composition of the sub-continental lithospheric mantle beneath the CPR, but comparing them to the general information already available might provide additional knowledge on the composition and evolution of the upper mantle. In contrast, Jeju Island is known as an intraplate volcano showing geochemical signatures of oceanic island basalt, whereas the island is located close to the eastern margin of the Eurasian plate which is known as a convergent plate margin, where Pacific and

Philippine plates are being subducted beneath the Eurasian Plate. Despite the fascinating geodynamic position of the island, peridotite studies from South Korea, particularly Jeju Island, are very rare (*e.g.* Choi *et al.*, 2002 and references therein). Hence, the general view on the evolution of the sub-continental lithospheric mantle here is still enigmatic. For this thesis we have selected a set of twenty peridotites, both common and special, to outline the general petrophysical feature of the shallow lithospheric mantle beneath the Island and to reveal special deformation and metasomatic processes which contributed to the composition and evolution of the upper mantle in East Asia.

This thesis is composed of the following major parts. (1) Because previous, especially, the early papers from the CPR described mainly the basic textural and geochemical features and solely presented "representative" xenoliths, only slight chemical and/or textural differences have been recognized. In this manuscript, we sought to provide additional information on the special rheological and textural and metasomatic processes and evolution of the lithospheric mantle beneath the central CPR by a detailed study on selected peridotite samples from a series of hundreds of xenoliths. By the reconstruction of pre- and post-entrapment evolution of silicate melt inclusions and fluid inclusions revealed from metasomatized peridotites of the CPR this study might contribute to the general knowledge of processes associated with high PT immiscibility and fluid entrapment. These peridotite xenoliths provide an opportunity to study the volatile content of such silicate melts, as well as the distribution of trace elements between melt and fluid during immiscibility in the upper mantle. These samples also show evidence regarding the presence of H_2O in the silicate melt and fluid inclusions, in addition to the more common and abundant CO_2. (2) Conversely, a reliable geochemical and textural database from peridotite xenoliths of Jeju Island, from which the general consequences on the evolution of the sub-continental lithospheric mantle can be drawn, is not yet available. Here, we present the first petrophysical analysis of "representative" and special mantle peridotites from the region along with their detailed major and trace element analysis to introduce deformation accompanied by geochemical evolution. (3) Comparison of the two peridotite series is necessary to reveal general features of the sub-continental lithospheric mantle and to distinguish them from those chemical and petrological features that are the result of the different geodynamic setting.

Methodology

3 deformed and 2 metasomatized peridotite xenoliths were selected for detailed study from the alkali basaltic outcrops of the Bakony-Balaton Highland Volcanic Field (central Carpathian Pannonian region), near the villages of Szigliget and Szentbékkálla. From Jeju Island (South Korea) 3 fine-grained mylonitic, 2 fine-grained porphyroclastic and 15 coarse grained protogranular-porphyroclastic peridotite xenoliths have been studied from three alkali basaltic localities at Sinsanri, Sangumburi and Jigriorem. 100-150 μm thick doubly polished thin sections and separated doubly polished mineral grains were made for the different analytical purposes.

Olivine crystallographic preferred orientation (CPO) from the deformed peridotites of the BBHVF and 7 selected peridotites from Jeju Island was measured using a JEOL JSM-5600 scanning electron microscope at Geosciences Montpellier of Montpellier University 2 (Montpellier, France). This SEM is equipped with an electron back-scattered diffraction (EBSD) system from HKL Technology using Channel5 software. Accelerating voltage of 17 kV, spot size of 78 and 25 mm working distance were used. Automatic orientation mapping was carried out in at least a 10×10 mm area of the studied xenoliths. Depending on grain size, a step size between 12-100 microns was used. Data were evaluated using Channel 5 software package.

Major element composition of constituent minerals in the two peridotite series and the residual glass of silicate melt inclusions in the metasomatized peridotites of the BBHVF was measured by different electron microprobes (JEOL Superprobe JXA-8600, JEOL Superprobe JX-8200, Cameca SX-50, Cameca SX-100) equipped with WDS detectors at the Department of Earth Sciences, University of Florence (Italy); Department of Geosciences, Virginia Polytechnic Institute and State University (USA); Bayerisches Geoinstitut (Germany); Department of Earth and Environmental Sciences, Pusan National University (South Korea); Department of Lithospheric Sciences, Vienna University (Austria) and Mineralogy and Petrology Research Group, University of Granada (Spain). Operating conditions were: accelerating voltage of 15-20 kV, beam current of 10-20 nA, beam size of 3-5 microns.

Trace element mineral chemistry of the xenoliths from the BBHVF was determined by LA-ICP-MS technique using an ELAN 6100 DRC quadrupole mass spectrometer (Institute of Isotope Geochemistry and Mineral Resources, ETH-Zürich, Switzerland) and an ELAN 6100 ICP-MS equipped with CETAC LSX-200 laser ablation system (Geocenter Copenhagen, Denmark), whereas an Agilent 7500ce octopol spectrometer (ORS), whereas GeoLas laser ablation system (Department of Geosciences, Virginia Polytechnic Institute and State University, USA) was used on clinopyroxenes of Jeju Island. The LA-ICP-MS analyses of bulk silicate melt inclusions of the metasomatized peridotites of the BBHVF were carried out using an ELAN 6100 DRC quadrupole mass spectrometer (Institute of Isotope Geochemistry and Mineral Resources, ETH-Zürich, Switzerland). The trace element composition of the coexisting fluid inclusions in these metasomatized peridotites was determined by an Agilent 7500ce octopol spectrometer (ORS) and GeoLas laser ablation system (Department of Geosciences, Virginia Polytechnic Institute and State University, USA).

For microthermometry of fluid inclusions of the peridotites of the BBHVF and Jeju Island, along with the microthermometry of the fluid bubble of silicate melt inclusions in the metasomatized peridotites of the BBHVF a Linkam THMS600 heating-cooling stage mounted on a Nikon Eclipse LV100POL polarizing microscope at Lithosphere Fluid Research Lab (LRG), Eötvös University Budapest (Hungary) was used.

A Jobin Yvon confocal-type Labram Raman instrument with a 532 nm Nd-YAG laser equipped with a CCD detector and 50× objective (Department of Organic Chemistry, Budapest University of Technology and Economics, Hungary) and a similar instrument with a 514 nm laser and 40×

microscope objective (Department of Geosciences, Virginia Polytechnic Institute and State University, USA) were used to analyze fluid composition of the studied peridotites.
The water determination of the minerals in the deformed peridotites of the BBHVF was carried out by Bruker IFS 28 type infrared microscope (Research School of Earth Sciences, The Australian National University, Australia) using unpolarized light and the calibration of Kovács *et al.* (2008) for quantification, whereas infrared analysis on the silicate melt and fluid inclusions along with that of the host minerals in metasomatized peridotites of the BBHVF was performed at ELETTRA Synchrotron Light Laboratory of Trieste (Italy).

Results

(1) Based on petrography, deformed spinel lherzolites with flattened tabular equigranular texture and metasomatized amphibole-bearing spinel lherzolites with coexisting silicate melt and fluid inclusions were selected from the BBHVF, whereas three fabric types were distinguished in the Jeju peridotite series forming a continuous transition from the coarse grained-protogranular-porphyroclastic to the fine grained mylonitic textures. Among these rock types, fine grained porphyroclastic and fine grained mylonitic peridotites have not been studied before from the Jeju Island.

(2) The results of fabric analysis suggest that the deformed peridotites of the BBHVF have extremely strong fabric and olivines possess strong crystallographic preferred orientation with [100]- and [001]-axes homogeneously dispersed in the plane of foliation and [010] showing distinct maximum perpendicular to it. Results of geochemical analyses suggest that these deformed peridotites have enriched trace element composition with spoon-shaped REE distribution. This is a common behavior of equigranular textured peridotites from the BBHVF (Downes *et al.*, 1992) and generally interpreted as a result of cryptic metasomatism of deformed peridotites.

(3) According to the previous results of deformation analysis on peridotite xenoliths from the central CPR at least two layers can be assumed in the lithospheric mantle having strong deformation patterns and lower equilibrium temperatures at shallower levels and showing the activation of only one slip system with high equilibrium temperatures at the bottom (Falus, 2004). The deformed peridotites studied here do not represent entirely, but might derive from the shallower level and most probably were deformed in a transpressional regime, as suggested based on experimentally deformed rocks. Transpressional regime is suggested to be typical forces acting on the lithosphere in collision or collision-and-escape type geodynamic environments, which was most likely to dominate during the Neogene formation of the Carpathian-Pannonian region, particularly beneath the central Pannonian Basin.

(4) Based on the trace element and REE patterns of the silicate melt inclusions and their host minerals, as well as the high-temperature crystallization for the clinopyroxene rims, which

enclose petrographically primary inclusions in the metasomatic peridotites of the BBHVF, a mantle-melt interaction can be assumed that occurred at elevated temperature resulted in partial melting of mantle clinopyroxene. This melting was triggered by an evolved reagent melt with trace element content similar to that of the host alkaline basalts, but was richer in SiO_2.

(5) Such a melt was likely formed by the interaction of an alkaline mafic melt rising from the asthenosphere with a portion previously metasomatized by probably a slab-derived melt. In the lithospheric mantle after initial clinopyroxene dissolution, the reacting melt likely became clinopyroxene-saturated. Due to cooling, crystallization of the clinopyroxene rims, entrapping drops of melt as silicate melt inclusions, took place. Simultaneously, the microfractures in orthopyroxenes and rarely spinels were filled with the evolved melt, which provided the glassy material (over)saturated in volatiles for the enclosed silicate melt inclusions during fracture healing.

(6) Coexisting silicate melt and fluid inclusions in the metasomatized peridotites of the BBHVF suggest that both petrographically primary and secondary inclusions were entrapped from an immiscible silicate melt and volatile phase at mantle conditions. The silicate melt inclusions show evolved major element composition with an overall enriched trace element pattern and significant (4-5 wt%) volatile (CO_2+H_2O) content. In contrast, the fluid inclusions are C-O-H-S dominated and most probably contain small amounts of silicate components. They possess trace element distribution similar to the silicate melt inclusions, which indicate that a small amount of dissolved silicate melt has a more pronounced effect on the trace element composition of CO_2-dominated fluid inclusions than the presence of H_2O. This might be an important conclusion for studies dealing with deep-seated fluid inclusions, especially if they were formed by immiscibility.

(7) Petrography and major element composition of the peridotite series of Jeju Island show that, apart from the obvious different fabric and grain size distribution; there is no significant difference between the peridotite xenoliths, which derived from the shallow sub-continental lithospheric mantle.

(8) Conversely, the trace element and REE composition of clinopyroxenes in the Jeju peridotite series indicate that three different chemical groups exist, which form continuous transition from the depleted La_N/Lu_N of 0.02 to the spoon-shaped enriched character with La_N/Lu_N of 6.37.

(9) Fabric analysis of the studied peridotites from Jeju Island shed light on the activation of the high temperature (010)[100] slip system, which is responsible for the deformation of the olivines, regardless of texture type. However, in the fine-grained porphyroclastic and fine grained mylonitic peridotites an additional deformation, probably at lower temperature and in a shear-dominated regime significantly weakened the originally strong fabric. This supports the idea that the Jeju peridotites represent a continuous series and suggests that finer the grain size, weaker the fabric.

(10) Comparing the results of trace element and fabric analysis a strong relationship is revealed between deformation and cryptic metasomatism as the fine grained porphyroclastic and fine grained mylonitic peridotites in every case show enriched trace element character, whereas the coarse grained protogranular-porphyroclastic peridotites are usually depleted. It is not clear whether the shear zones, represented by the fine grained peridotites, encouraged preferential melt infiltration or whether the shear zone is the result of deformation, lubricated by metasomatic agents. Similar conclusion was drawn by Downes (1990), who found relationship between geochemical enrichment and deformation in many mantle peridotites worldwide.

(11) The composition and evolution of the fluid inclusions in the Jeju peridotite series and in those of the CPR strongly suggest that fluid inclusions trapped at deep lithospheric mantle conditions contain small, thus significant amounts of H_2O. These observations support our assumption that small amounts of H_2O exist as a thin film on the walls of many high-density CO_2-rich fluid inclusions, and its detection is prevented by the inadequacy of currently used analytical techniques. Therefore, the presence of water in deep-seated fluid inclusions is not the special feature of the upper mantle, but rather reflects the general composition of any fluid inclusion from a sub-continental lithospheric setting.

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